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13. ABSTRACT (Maximum 200 words)

The goal of the proposed work is to investigate the potential advantages of the InGaN channel as a host of the 2DEG and to address the material related problems facing this ternary alloy in the AlGaN/InGaN MODFET structure. The impact on addressing these materials issues on the AlGaN/InGaN MODFET device performance will be systematically investigated and compared with the corresponding GaN 2DEG.

There are several issues that were investigated, that are related to the properties of InGaN and AlGaInN material systems. These properties are concerned with the strain and its effects on the band structure, recombination process, band offset and piezoelectric fields and 2DEG.

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ALGAN/INGAN NITRIDE BASED MODULATION DOPED FIELD EFFECT TRANSISTOR:

A. INTRODUCTION:

The goal of the proposed work is to investigate the potential advantages of the InGaN channel as a host of the 2DEG and to address the material related problems facing this ternary alloy in the AlGaN/InGaN MODFET structure. The impact on addressing these materials issues on the AlGaN/InGaN MODFET device performance will be systematically investigated and compared with the corresponding GaN 2DEG.

There are several issues that were investigated, that are related to the properties of InGaN and AlGaInN material systems. These properties are concerned with the strain and its effects on the band structure, recombination process, band offset and piezoelectric fields and 2DEG.

B. ACHIEVEMENTS:

We did investigate the following research areas to achieve the goals of the proposed work.

1.Critical layer thickness and phase separation in InGaN alloys

1.1 Determination of the critical layer thickness in the InGaN/GaN heterostructures

We present an approach to determine the critical layer thickness in the $In_xGa_{1-x}N$/GaN heterostructure based on the observed change in the photoluminescence emission as the $In_xGa_{1-x}N$ film thickness increases. From the photoluminescence data, we identify the critical layer thickness as the thickness where a transition occurs from the strained to unstrained condition, which is accompanied by the appearance of deep level emission and a drop in band edge photoluminescence intensity. The optical data that indicate the onset of critical layer thickness, was also confirmed by the changes in $In_xGa_{1-x}N$ surface morphology with thickness, and is consistent with x-ray diffraction measurements. C. Parker, J. Roberts, S. Bedair, M. Reed, S. Lui, N. El-Masry, Appl. Phys. Lett. **75**, 2776 (1999)

1.2 Critical layer thickness determination of GaN/InGaN/GaN double heterostructures

We report on the critical layer thickness of GaN/$In_xGa_{1-x}N$/GaN double heterostructures in the composition range $0<x<0.16$. The evolution of the photoluminescence spectra and the electrical properties of the $In_xGa_{1-x}N$ well were monitored as its thickness was increased for a given % InN. Due to compressive stress and possible quantum-size effects, the emission energy from thin InGaN wells is blueshifted relative to thicker wells of a given % InN. The transition from the blueshifted emission of strained InGaN to redshifted emission of relaxed InGaN is also accompanied by dramatic changes in film conductivity and mobility. The thickness at which the onset of relaxation occurs is deemed the critical layer thickness of the $In_xGa_{1-x}N$ film. M.J. Reed, N. El-Masry, C. A. Parker, J.C. Roberts and S. M. Bedair, Appl. Phys. Lett, **77**, 4121 (2000)

1.3 Phase separation and ordering coexisting in InxGa1–xN grown by metal organic chemical vapor deposition

We have recently reported the occurrence of phase separation in $In_xGa_{1-x}N$ samples with x>0.25. Theoretical studies have suggested that $In_xGa_{1-x}N$ can phase-separate asymmetrically into a low InN% phase and an ordered high InN% phase. In this letter, we report on the existence of simultaneous phase separation and ordering of $In_xGa_{1-x}N$ samples with x>0.25. In these samples, phase separation was detected by both transmission electron microscopy selected area diffraction (TEM-SAD) and x-ray diffraction. Ordering was detected by both imaging and TEM-SAD. M.K. Behbehani, E.L. Piner, S.X. Lui, N. A. El-Masry and S.M. Bedair, Appl, Phys Lett **75**, (1999)

1.4 Relaxation of InGaN Thin Layers Observed by X-Ray and Transmission Electron Microscopy Studies

Double-crystal and triple-axis X-ray diffractometry and transmission electron microscopy have been used to characterize the microstructure, the strain and composition of InGaN layers grown on GaN by metalorganic chemical vapour deposition (MOCVD). Three different samples with increasing In composition have been studied, all grown on GaN deposited on sapphire either with GaN or AlN buffer layer. It was found that the samples with nominal 28% and 40% InN content consists of two sub-layers; one closer to the interface with the GaN almost fully strained and the second relaxed layer where many planar defects have been found. The sample with the highest nominal Indium concentration (45%) grown on GaN with AlN buffer layer was fully relaxed and planar defects were observed in all layer. For partially strained layers the bending of samples was detected. Liliental-Weber, Z; Benamara,M; Washburn,J; Piner, E; Roberts, J; and Bedair, S.M., J. Electron. Mat. **30** 439, 2001

1.5 Ultraviolet Raman study of A1(LO) and E2 phonons in InxGa1–xN alloys

We report on ultraviolet Raman spectroscopy of $In_xGa_{1-x}N$ thin films grown on sapphire by metal-organic chemical vapor deposition. The A_1(LO) and E_2 phonon mode behavior was investigated over a large compositional range ($0<x<0.50$). Compelling evidence is presented for one-mode behavior for the A_1(LO) phonon, and data suggestive of two-mode behavior are presented for the E_2 phonon. D. Alexon, L.Bergman, R. Nemanich, M. Dutta, M. Strscio, C. Parker, S.M. Bedair, N. El-Masry, F. Adar, J Appl. Phys., **89**, 798, (2001)

2. AlInGaN Quaternary Alloys

2.1 High optical quality AlInGaN by metalorganic chemical vapor deposition

We report on the metalorganic chemical vapor deposition of the quaternary alloy AlInGaN. We found it desirable to grow quaternary films at temperatures greater than 855 °C in order to suppress deep level emissions in the room-temperature photoluminescence. Details of the conditions necessary to grow $In_{0.1}Ga_{0.9}N$ at 875 °C are presented. Strained and relaxed

AlInGaN films were grown with good optical and structural properties for AlN compositions up to 26% and InN content up to 11%. The effects of strain were observed by a difference in the band gap between thin and thick films with the same compositions. The potential impact of the use of quaternary films is discussed regarding strain engineering for the improvement of present device designs. M. Aumer, S. F. LeBeouf, F. McIntosh and S.M. Bedair, Appl. Phys. Lett. **75**, 3315 (1999)

3. Self Assembled Superlattice Structures

3.1 Self-assembled AlInGaN quaternary superlattice structures

When an AlInGaN quaternary alloy is grown by metalorganic chemical-vapor deposition under certain growth conditions, a self-assembled superlattice structure is obtained. The superlattice structure is made of quaternary layers with different AIN and InN compositions. Transmission electron microscopy data show that the superlattice periodicity is regular with an individual layer thickness that depends on the growth conditions. Secondary ion mass spectrometry measurements show that the layers' composition alternate between high-AIN and InN content and low-AlN and-InN content, while the in-plane lattice constant remains constant for both layers. A model is presented as a preliminary effort to explain these results. N. El-Masry, M.K. Behbehani, M. Aumer, J. Roberts, and S.M. Bedair, Appl. Phys. Lett., **616** (2001)

4. Piezoelectric Effect in Strained AlInGaN Material System

4.1 Effects of tensile and compressive strain on the luminescence properties of AlInGaN/InGaN quantum well structures

We report on the luminescence properties of AlInGaN/$In_{0.08}Ga_{0.92}N$ quantum wells (QWs) subjected to a variable amount of lattice mismatch induced strain, including wells with zero strain, compressive strain, and tensile strain. The primary peak emission energy of a 3 nm $In_{0.08}Ga_{0.92}N$ QW was redshifted by 236 meV as the stress in the well was changed from –0.86% (compressive) to 0.25% (tensile). It was also found that the photoluminescence intensity of quantum wells decreased with increasing strain. A lattice matched 9 nm QW exhibited a luminescence intensity that is three times greater than its highly strained counterpart. The potential applications of this strain engineering will be discussed. M.E. Aumer, S.F. LeBoeuf, S.M. Bedair, M. Smith, J. Lin and H. Jiang, Appl. Phys. Lett. **77**, 821 (2000)

4.2 Critical layer thickness determination of GaN/InGaN/GaN double heterostructures

We report on the critical layer thickness of GaN/$In_xGa_{1-x}N$/GaN double heterostructures in the composition range $0<x<0.16$. The evolution of the photoluminescence spectra and the electrical properties of the $In_xGa_{1-x}N$ well were monitored as its thickness was increased for a given % InN. Due to compressive stress and possible quantum-size effects, the emission energy from thin InGaN wells is blueshifted relative to thicker wells of a given % InN. The transition from the blueshifted emission of strained InGaN to redshifted emission of relaxed

InGaN is also accompanied by dramatic changes in film conductivity and mobility. The thickness at which the onset of relaxation occurs is deemed the critical layer thickness of the $In_xGa_{1-x}N$ film. S.F. LeBouef, M.E. Aumer, S.M.Bedair, Appl. Phys.Lett., **77**, 97 (2000)

4.3 Strain-induced piezoelectric field effects on light emission energy and intensity from AlInGaN/InGaN quantum wells

We report on the effects of the piezoelectric field and well width on the transition energy and intensity for InGaN quantum well structures with GaN or AlInGaN quaternary barriers. It was found that the emission energy of compressively strained $GaN/In_{0.08}Ga_{0.92}N$ quantum wells exhibits a strong well width dependence not accounted for by quantum confinement subband energy shifting alone. However, for unstrained quantum well layers with quaternary barriers, no emission energy dependence on width was observed due to the elimination of the piezoelectric field, which was measured to be at least 0.6 MV/cm for the strained quantum wells. Furthermore, the unstrained quantum wells demonstrated a higher intensity than their strained counterparts for all quantum well widths investigated. The current data will help clarify the origin of emission in InGaN quantum wells. Aumer, M, Lebouef, S.M. Bedair, Appl. Phys. Lett. **79**, 3803 (2001).

4.4 Effects of tensile, compressive, and zero strain on localized states in AlInGaN/InGaN quantum-well structures

The recombination dynamics of optical transitions as well as strain effects in $AlInGaN/In_{0.08}Ga_{0.92}N$ quantum wells (QWs) were studied. QW emission energy, photoluminescence decay behavior, photoluminescence emission line shape, and nonradiative recombination behavior were found to be strong functions of strain as well as localization. The degree of carrier localization was inferred by modeling several aspects of optical behavior obtained from variable temperature time-resolved photoluminescence experiments. According to the modeling results, the degree of localization was found to be a minimum for unstrained QWs and increased as either tensile or compressive strain increased, indicating that InGaN QW microstructure is a function of the lattice-mismatch-induced strain experienced during deposition. M. Aumer, S. LeBouef, B. Moody, S.M Bedair, H.X. Jiang, Appl. Phys. Lett. **80**, 3099 (2002)

5. Ultraviolet-Visible Metal-Semiconductor-Metal Photodetectors Fabricated from InxGa1-xN (0 ≤ x ≤ 0.13)

Metal-semiconductor-metal (MSM) photodetectors have been fabricated on InxGa1−xN epitaxial films grown by metalorganic chemical vapor deposition within the composition range 0 ≤ x ≤ 0.13. The dark current and spectral response were measured for devices with a varying In mole fraction x. The devices, which had nominal finger widths and finger spacing of 5 μm, were biased with modest voltages in the range 2 ≤ Vbias ≤ 5 V. In general, turn-on wavelength and dark current increased with increasing x. Turn-on wavelengths ranged from λ = 370 nm to 430 nm and dark current densities ranged from Idark = 2 × 10−2 A/cm2 (Vbias = 5 V, ≃ 0.05) to 9 × 104 A/cm2 (Vbias = 2 V, ≃ 0.13) depending on the In content, x, of the device active area. J. C. Roberts, C. A. Parker, J. F. Muth, S. F. Leboeuf, M. E. Aumer, S. M. Bedair, and M. J. Reed, J. Elec. Mat. **81**, 1 pp. L1-L6

C. LIST OF PUBLICATIONS:

1. C. Parker, J. Roberts, S. Bedair, M. Reed, S. Lui, N. El-Masry, "Determination of the critical layer thickness in the InGaN/GaN heterostructures" Appl. Phys. Lett. **75**, 2776 (1999)

2. M.J. Reed, N. El-Masry, C. A. Parker, J.C. Roberts and S. M. Bedair, "Critical layer thickness determination of GaN/InGaN/GaN double heterostructures", Appl. Phys. Lett, **77**, 4121 (2000)

3. M.K. Behbehani, E.L. Piner, S.X. Lui, N. A. El-Masry and S.M. Bedair, "Phase separation and ordering coexisting in InxGa1–xN grown by metal organic chemical vapor deposition", Appl, Phys Lett **75**, (1999)

4. Liliental-Weber, Z; Benamara,M; Washburn,J; Piner, E; Roberts, J; and Bedair, S.M., "Relaxation of InGaN Thin Layers Observed by X-Ray and Transmission Electron Microscopy Studies" J. Electron. Mat. **30** 439, 2001

5. D. Alexon, L.Bergman, R. Nemanich, M. Dutta, M. Strscio, C. Parker, S.M. Bedair, N. El-Masry, F. Adar, "Ultraviolet Raman study of A1(LO) and E2 phonons in InxGa1–xN alloys" J Appl. Phys., **89**, 798, (2001)

6. M. Aumer, S. F. LeBeouf, F. McIntosh and S.M. Bedair, "High optical quality AlInGaN by metalorganic chemical vapor deposition" Appl. Phys. Lett. **75**, 3315 (1999)

7. N. El-Masry, M.K. Behbehani, M. Aumer, J. Roberts, and S.M. Bedair, "Self-assembled AlInGaN quaternary superlattice structures", Appl. Phys. Lett., **79**, 1616 (2001)

8. M.E. Aumer, S.F. LeBoeuf, S.M. Bedair, M. Smith, J. Lin and H. Jiang, "Effects of tensile and compressive strain on the luminescence properties of AlInGaN/InGaN quantum well structures" Appl. Phys. Lett. **77**, 821 (2000)

9. S.F. LeBouef, M.E. Aumer, S.M.Bedair, "Critical layer thickness determination of GaN/InGaN/GaN double heterostructures" Appl. Phys.Lett., **77**, 97 (2000)

10. Aumer, M, Lebouef, S.M. Bedair, "Strain-induced piezoelectric field effects on light emission energy and intensity from AlInGaN/InGaN quantum wells", Appl. Phys. Lett. **79**, 3803 (2001).

11. M. Aumer, S. LeBouef, B. Moody, S.M Bedair, H.X. Jiang, "Effects of tensile, compressive, and zero strain on localized states in AlInGaN/InGaN quantum-well structures", Appl. Phys. Lett. **80**, 3099 (2002)

12. J. C. Roberts, C. A. Parker, J. F. Muth, S. F. Leboeuf, M. E. Aumer, S. M. Bedair, and M. J. Reed, "Ultraviolet-Visible Metal-Semiconductor-Metal Photodetectors Fabricated from InxGa1-xN ($0 \leq x \leq 0.13$)", J. Elec. Mat. **81**, 1 pp. L1-L6

D. GRADUATE STUDENT SUPPORT:

1. Mike Aumer	Ph.D.	2001
2. Steve LeBoeuf	Ph.D.	2002
3. Chris A. Parker	Ph.D.	2003
4. Mason J. Reed	Ph.D.	2004 (expected)

E. INVENTION:

None